

Methods for Identifying and Optimizing Catalysts
~~CHEMICAL PROCESSING MICROSYSTEMS, DIFFUSION-MIXED~~
~~IN PARALLEL-FLOW MICROREACTORS~~
~~MICROREACTORS AND METHODS FOR PREPARING AND USING SAME~~

is a divisional of 09/518,794, filed 3/3/00, now USA 6,749,814 which
5 This application claims priority to commonly owned, co-pending U.S. patent
application Ser. No. 60/122,704 filed March 3, 1999 entitled "Chemical Processing
Microsystems, Diffusion-Mixed Microreactors and Methods for Preparing and Using
Same", which is hereby incorporated by reference for all purposes.

10 BACKGROUND OF THE INVENTION

The present invention relates generally to the field of combinatorial chemistry
and, in preferred applications, to the field of combinatorial materials science. In
particular, the invention relates to systems and methods employing microfluidic devices
in chemical processes, for characterizing and optimizing such chemical processes and for
15 identifying materials that enhance such chemical processes. Preferred embodiments of
the invention relate to microchemical processing systems, to diffusion-mixed
microreactors, and to methods for identifying or optimizing heterogeneous catalysts.

Combinatorial chemistry refers generally to methods for synthesizing a collection
of chemically diverse materials and to methods for rapidly testing or screening this
20 collection of materials for desirable performance characteristics and properties.
Combinatorial chemistry approaches have greatly improved the efficiency of discovery
of useful materials. For example, material scientists have developed and applied
combinatorial chemistry approaches to discover a variety of novel materials, including
for example, high temperature superconductors, magnetoresistors, phosphors and
25 catalysts. See, for example, U.S. Patent No. 5,776,359 to Schultz et al. In comparison to
traditional materials science research, combinatorial materials research can effectively
evaluate much larger numbers of diverse compounds in a much shorter period of time.
Although such high-throughput synthesis and screening methodologies are conceptually
promising, substantial technical challenges exist for application thereof to specific
30 research and commercial goals.

Microfluidics refers generally to the field of miniaturized fluidic systems.
Microfluidic systems have been designed to perform similar tasks as larger scale
commercial fluid systems, and have included a number of different microcomponents
such as fluid-distribution channels, valves, pumps, motors, mixers, heat-exchangers,

sputtering, ion plating), chemical vapor deposition, plasma-assisted chemical vapor deposition, electrodeposition, electrochemical deposition, coating techniques (e.g., spray drying, spray coating, pyrolysis), and solution-based techniques (e.g., sol-gel, impregnation; precipitation), among others. The film can also be formed by *in situ* growth at a substrate surface, by diffusion of the material into a substrate surface, or by conversion of the substrate material (e.g., thermal oxidation). Such approaches and others are discussed in detail in Bunshah, Handbook of Deposition Technologies for Films and Coatings, 2nd Ed., Noyes Publications (1994), and references cited therein. The candidate materials may be applied in discrete, individually addressable regions using mechanical or chemical masking approaches. For example, mechanical masks or shutters can be used in connection with many of the aforementioned deposition techniques to create an array of films in a desired arrangement. Distinct regions of candidate materials may also be formed using film-formation approaches that are or can be controlled to be region-selective – without masking. Spray drying and electrochemical deposition approaches are exemplary region-selective approaches. Different candidate materials may alternatively be applied contiguous to each other. The array can comprise, for example, a contiguous composition gradient of two or more components. Contiguous natural composition gradients can be formed, for example, by multiple-target vapor deposition approaches. See, e.g., Hanak et al., Optimization Studies of Materials in Hydrogenated Amorphous Silicon Solar Cells, Photovoltaic Solar Energy Conference, Berlin (1979), and van Dover et al., Discovery of a Useful Thin-Film Dielectric Using a Composition-Spread Approach, Nature, Vol. 392, No. 12, pp. 162-164 (1998). Contiguous controlled gradients can be formed, for example, by orchestrated (e.g., programmed) masking or shuttering approaches with multi-target deposition, such as those disclosed in copending U.S. patent application Serial No. 09/237,502 filed January 26, 1999 by Wang et al.

Preferred approaches for forming an array of candidate materials include vapor deposition techniques disclosed in U.S. Patent No. 5,776,359 to Schultz et al., sol-gel solution-based techniques disclosed in commonly-owned co-pending U.S. patent application Serial No. 09/156,827, filed January 18, 1998 by Giaquinta et al., electrochemical deposition techniques disclosed in commonly-owned co-pending U.S. patent application Serial No. 09/119,187, filed July 20, 1998 by Warren et al., and *in situ* impregnation techniques for creating arrays of supported catalysts as disclosed in commonly-owned co-pending U.S. patent application Serial No. _____, filed _____.

Lx
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Lg

March 1, 2000 by Lugmair *et al.*, each of which is incorporated by reference for all purposes. The combinatorial library embodied in the array of candidate materials is preferably designed with the assistance of library design software such as LIBRARY STUDIO™ software (Symyx Technologies, Inc., Santa Clara, CA). Preparation of the
5 arrays can be advantageously effected using automated liquid handling robots (e.g., CAVRO Scientific Instruments, Inc.), under control of software such as IMPRESSIONIST™ software (Symyx Technologies, Inc.).

The amount of an individual candidate material deposited as a film (or otherwise included) on a particular portion of the array is not limiting to the invention. The
10 required amount will vary depending upon the required surface area of the film and the required thickness of the film, each of which will, in turn, vary depending upon the chemical process of interest, the geometry of the microreactor, and the required residence time or contact time of reactants in the microreactor, among other factors. In general, the amount of an individual candidate material is typically not more than about 25 mg,
15 preferably not more than about 10 mg, and can be not more than about 7 mg, not more than about 5 mg, not more than about 3 mg and not more than about 1 mg. In preferred embodiments, the amount of an individual candidate material can range from about 0.1 µg to about 100 mg, preferably from about 1 µg to about 10 mg; more preferably from about 10 µg to about 10 mg and most preferably from about 100 µg to about 1 mg.

While an array of one or more films is advantageously employed in connection
20 with the present invention, other array configurations can also be employed to supply the two or more solid-phase candidate materials to a plurality of microreactors. The array can comprise, for example, the candidate materials loaded into the microreactors in bulk form, or as bonded to or linked to porous materials or to microparticles. With reference
25 again to Figure 3, the array can comprise, for example, a substrate 110 having a plurality of wells 130 formed in an exposed surface 112 of the substrate (e.g., Fig. 3E, Fig. 3G) or having a plurality of apertures 140 extending between first and second substantially parallel surfaces 111, 112 of the substrate 110 (e.g., Fig. 3F, Fig. 3H). Such a well 130 or an aperture 140 can comprise a porous material 122 (e.g., Fig. 3E, Fig. 3F) to which a
30 particular candidate material is bonded, preferably covalently bonded. Exemplary porous materials include quartz, glass or alumina, etched microchannels or glass plates, diatomaceous earth, etc. As another alternative, a well 130 or an aperture 140 can comprise microparticles 124, typically referred to in the art as "latex particles" or "beads", to which a particular candidate material is bonded, and preferably covalently